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Relation of Peak Expiratory Flow Rates and Symptoms to Ambient Ozone

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ABSTRACT. The temporal association between peak expiratory flow rates (PEFRs) and ambient ozone (O_3) was studied in a group of 287 children and 523 nonsmoking adults in Tucson. In children, noon PEFRs were decreased on days when there was a higher O_3 concentration; children with physician-confirmed asthma experienced the greatest decrease in noon PEFR. Evening PEFR levels were also significantly related to O_3 in children, especially asthmatics. Among adults, evening PEFRs were decreased in asthmatics who spent more time outdoors on days when O_3 levels were higher. After we adjusted for covariates, significant effects of interactions of 8-h O_3 levels with particulate matter (PM_{10}) and temperature on daily PEFR were found. There was some overnight effect of 8-h O_3 on morning PEFRs. In general, the respiratory response to low-level ambient O_3 is acute, occurs more in asthmatics, and increases as temperature and PM_{10} increase.

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SHORT-TERM lung function declines that result from exposure to relatively low concentrations of ozone (O_3) have been reported in many studies,[1-16] and these declines have been reviewed very recently by Lippmann.[1] Most of the evidence is derived from exposure chamber studies,[7-9,11] in which changes have been observed in subjects who are exposed to O_3 concentrations that range from 120 to 180 ppb for 1- to 3-h periods. Studies of children who attend summer camps,[2,3] of school-age children,[4] and of children and adolescents in Tucson[5] have reported associations between lung function and ambient O_3 (1-h maximum concentrations below 120 ppb). A correlation of lung function with ambient O_3 exposure has been reported in a few adult studies.[5,6] Recent laboratory experiments in which O_3 exposure lasted 6.6 h[7,8] indicate that duration of exposure is an important factor in producing a response. Therefore, the health effects of relatively low O_3 levels that persist

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for several hours in an atmosphere[9] may be more pronounced than expected, based on the measured 1-h maximum O_3 concentration. Also, a cumulative effect of O_3 concentration that was elevated during a few consecutive days was suggested by the summer camp data.[10]

In this study, we analyzed the relationship of peak expiratory flow rates (PEFRs) to ambient O_3 concentration. The latter was estimated as (a) the daily 1-h maximum and the 8-h maximum moving average and (b) the 8-h average maximum from values obtained on preceding days, including the mean of these values for the previous 4 d. In this study period, the maximum ambient O_3 concentrations were relatively low, i.e., the 1-h maximum never exceeded 92 ppb. Daily variations of PEFRs and symptoms were evaluated, and PEFRs of children and nonsmoking adults were examined. The subjects were from a community population in Tucson.

The purpose of this study was to evaluate the temporal pattern of lung function response to O_3 exposure. Specific aims were to estimate if (a) detectable PEFR changes in real-life situations are related to short-term or to prolonged exposure, (b) if the changes persist overnight, and (c) if there is a cumulative effect of the exposure that lasts a few consecutive days. Furthermore, we evaluated possible differences in these responses that were attributable to asthma or other respiratory diseases. Also, we evaluated O_3 interactions with additional exposures to passive smoking to outdoor particulate matter and/or to outdoor temperature. In response to the question of possible seasonal adaptation to the exposure,[11] we tested to determine if responses to O_3 exposure in spring were greater than in other seasons.

Methods

The detailed description of the study population and methods of data collection have been presented previously.[12] Briefly, the population for this study was derived from the municipal employees of the local county government and their families. This population included a wide spectrum of socioeconomic status (SES) and was representative of SES within the employed population in this geographic area. It also had fairly representative distributions of age, sex, and ethnic groups. Information gleaned during the initial screening with questionnaires was used to select a sample of households. It was important to include a sufficient number of children in the sample; therefore, only the households with children 5–15 y of age were eligible for this study. The peak flow measurements analyzed in this study were collected during 2-wk periods, from May 1986 through November 1988, and a fairly uniform distribution of subjects was studied in each season.

Basic individual characteristics were determined from modified standard health questionnaires[13]; additional sections were included that identified normal activity patterns and symptomatic responses to environmental factors. Adults completed the questionnaires for themselves and for their children. Peak expiratory flow rates were measured with mini-Wright peak flow meters, a description and discussion of which has been presented previously.[5,14-17] Tests were performed during four or fewer time periods each day: (1) morning (on rising), (2) near noon, (3) evening (4–7 P.M.), and (4) prior to going to bed. Each subject was trained to use the peak flow meter, and they were requested to perform three tests for each time period (morning, noon, evening, bed) and to record the largest value in their diary. Children's tests were supervised by an adult, who also recorded the results. Only one peak flow meter was assigned to each household. This prevented measurement at noon for many of the family members who were away from their homes at noon. We sought to eliminate a possible learning effect; therefore, data were eliminated from the initial 2 d of observation (which demonstrated improvement), thus limiting the observation period to 12 d. In this analysis, we used the data from the morning, noon, and evening measurements only. Daily diaries were also used to record symptoms, medication usage, and activity patterns, in a manner used and described previously.[5,12,17]

Outdoor data for O_3 were obtained from the Pima County Department of Environmental Quality (PCDEQ). An EPA-sponsored inventory of O_3 in the basin produced quite uniform values, which accords with what has been reported previously.[6] Therefore, it was not deemed necessary to include more than three monitoring locations in the basin to guarantee accurate outdoor exposure estimates. The hourly averages from the PCDEQ chemiluminescent monitors were obtained on tape. These files were processed to identify the O_3 records for each study day and to determine the maximum 1-h concentration and the maximum 8-h moving average of 1-h values for each location. Stations for which more than 3 h of O_3 measurements were missing between 9 A.M. and 7 P.M. were excluded from the analysis for that day. The 8-h moving average was not calculated if more than 2 hr of measurements were missing from that 8-h period. The maximum concentrations differed slightly among the monitoring stations, but the correlation of the measurements was very high (correlation coefficient between 0.64 and 0.91 for each pair of the stations for 1-h and 8-h maxima). Thus, the maximum 1-h and 8-h average values from the three stations were used to represent the O_3 concentrations for all subjects who were studied on a given day. For each day of the study, the mean of the maximum 8-h average O_3 concentrations for the 4 preceding days was calculated to be an index of cumulative exposure. Because indoor O_3 concentrations were between 0 and 0.035 ppm,[5] as determined by the use of identical Dasibi monitors as were used outdoors, O_3 exposure was based on outdoor levels, which were adjusted for time outdoors.

During part of the study period, data regarding ambient concentrations of particulate matter (less than 10 μm diameter [PM_{10}]) were collected daily at one monitoring station, and the data were used in the analysis.

The relationship of PEFR values to O_3 levels was analyzed with two statistical models. A second statistical model was used to account for the evident autocorrelation of PEFR measurements in each subject (relative to

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O_3). In this version of the random-effects longitudinal model,[18,19] the within-subjects' observations include a first-order autoregressive serial correlation component and random observational errors. This model can be applied to data collected by an unequal number of observations per subject, which can be accomplished at unequal intervals. Examination of PEFR measurements indicated that there was no systematic trend in the daily PEFR values of each subject during the 12-d observation period (after data from the 2 initial days were excluded). Thus, the within-subject (random) effect was constant, and we have modeled the effects of O_3 and other covariables as population parameters. The model allows inclusion of both fixed and time-dependent covariates. In this analysis, the constant covariates were gender (1 = female, 0 = male); age; subject-reported asthma status (1 = current disease diagnosed by a doctor, other = 0); exposure to environmental tobacco smoke (ETS = 1 if there was any smoking in the household during the week of PEFR measurements, 0 if no smoking); work in dusty jobs or exposure to gases or fumes at work during the past year (yes = 1, no = 0); and spring season (March = 1, otherwise = 0). The time-dependent covariates were O_3 concentration; time spent outdoors during the day; maximum outdoor temperature; presence of acute respiratory illness or symptoms during the day (sore throat, cough, wheezing or whistling in the chest, shortness of breath with wheezing, chest tightness [ARI = 1 if yes]); and PM_{10} concentration. Among the time-dependent covariates, there were also the indicator (0, 1) variables that corresponded to time of the day when the PEFR measurement was taken. The main effects of these variables represented the natural diurnal variability of PEFR values.[17,20,21] Interactions of these variables with other factors indicate the additional effect of the factor on the PEFR measured at a given time of day (e.g., the term "O_3 * evening" corresponds to the change in evening PEFR measurement that results from a unit change in O_3 concentration). The interaction of an indicator (0, 1) variable with O_3 corresponds to the additional effect when the factor is present (e.g., the term "O_3 * asthma" reflects an additional change in PEFR that results from O_3 in asthmatics). Interaction terms were evaluated with all respective main effects included in the model. In cases where the elimination of a nonsignificant main effect did not affect the value of the coefficient that corresponded to the interaction term, the main effect was removed from the final model. This would occur when an effect was limited to a subgroup of the population, and all other subjects were included in a reference group.

The analysis was performed separately for subjects who were aged 6–15 y and for those who were more than 15 y of age. We also studied separately the effects of O_3, which were estimated as the maximum 1-h and 8-h mean values. This was done to limit the number of factors in a single model and to avoid the consideration of co-linear factors in one model (the correlation of 1-h and 8-h values was 0.88). Several different random effects models were tested (fitted to the data), which assured selection of the models that best described the relationship of PEFR to O_3 concentration and its interactions with other factors (accounting for significant confounding effects). The significance of terms of the models (i.e., model parameters) was tested by the log-likelihood ratio test; the significance level was $p < .05$, and p values between .05 and .10 were considered to be borderline significant. We present the "best" parsimonious models. The terms absent in the models presented were found to be nonsignificant ($p > .10$) or did not modify the relationship between PEFR and O_3.

A second statistical method, multifactorial analysis of covariance (ANCOVA),[5] was used to analyze day-to-day changes in daily average PEFRs and symptom prevalence rates (the dependent variables) in relation to 8-h O_3 values on the same and previous days (lags of 0 and 1). For this purpose, we used data from 1 007 days of observation, compiled from the 2-wk test periods, for all subjects. Mean daily averages were calculated specifically for morning and evening PEFRs. The distributions of daily symptom prevalence rates were skewed; therefore, log transforms of the rates were used as dependent variables. Demographic and social confounding or covariables included the mean number of hours spent outdoors and the proportions of the population on each day that were in each of the following categories: male, under age 15 y, lived in households (HH) where the head of HH obtained less than a high-school education (SES), smoked, exposed to environmental tobacco smoke (ETS) or to gas cooking in the home, worked away from home or were at school, and worked in jobs with dust or fume exposures. Nitrogen dioxide, PM_{10}, and weather measurements were also used as co- or confounding variables. Meteorological covariables included season, daily maximum and minimum temperatures, average wind speed, and average dew point. The ANCOVA yielded adjusted values, expressed changes from the grand mean of the dependent variable (e.g., PEFR), for explanatory variables as independent effects (adjusted for each other and for covariables), and for interactions (adjusted for all other variables).

Results

The peak expiratory flow values were measured in 287 children (mean age = 10.4 y) and 523 adult nonsmokers (mean age = 40.1), for whom acceptable O_3 concentration data had been collected at least 1 d. In both groups, the proportion of males was similar (53% and 54%, respectively). The proportion of children who lived in homes inhabited by smokers was higher than the proportion who lived with adult nonsmokers (44% versus 33%, respectively). More children than adults reported a current asthma condition diagnosed by a doctor (13% versus 9%, respectively). Acute respiratory illnesses and symptoms were recorded for 15% and 14% of the person-days among children and adults, respectively. Children reported that they remained outdoors an average of 2.9 h per person-day, and adults reported 2.7 h per person-day. The mean maximal daily outdoor temperature was 87 °F (30 °C) per person-day. The maximum level of PM_{10}, recorded

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during the study days, was 187 $\mu g/m^3$ (mean = 42 $\mu g/m^3$).

During the study period (i.e., during collection of the PEFR data), the O_3 maximum 1-h concentrations ranged from 15 to 92 ppb (mean ± standard deviation = 55 ± 14 ppb). Moving average maximum 8-h concentrations ranged from 9 to 82 ppb (46 ± 13 ppb [Fig. 1]). The highest concentrations of O_3 were usually attained by noon on each day and persisted for several hours. On many days, sharp declines in O_3 levels were noted only after 6 P.M.

Results of random effects models. Data for at least 6 d, during which at least 12 observations were made, were available for 78% of the children. All children combined provided 5 483 observations. Separate models were used for adults so that the effects of O_3 on evening and on noon PEFR levels could be evaluated. Morning or evening data for at least 6 d (12 or more data points) were available for 74% of the adults. There were 8 122 morning or evening PEFR measurements for all adults. Noon measurements were missing more frequently than measurements performed at other times of the day. Personal PEF meters were available for only 50% of person-days, and PEFR values were measured in the morning and evening, thus yielding only 6 852 paired observations to use for the estimation of effects of O_3 on noon PEFR levels in adults.

The estimated effects of O_3 on PEFRs are presented in Tables 1 (children) and 2 (adults). In all models, there were significant effects of the time of day when PEFR measurements were performed, which reflected a natural increase in PEFR during the day, followed by its overnight decline. In both children and adults who had currently diagnosed asthma, the diurnal variability of PEFRs was significantly greater, and the morning levels were usually lower than levels found in nonasthmatics.

The noon PEFR levels in children were lower on days with higher 1-h maximum O_3 levels (Table 1, Model I). The estimated effect of 100 ppb of O_3 in nonasthmatic children (−11.9 l/min) was equivalent to 3.8% of their mean PEFR level, which was as if the absolute value of the natural increase between morning and noon did not occur. (Given that morning is the basis for comparison, the change is calculated by summing products of coefficients times variables, adding the constant, and then computing an effect/mean ratio. The natural increase in the absence of an O_3 effect is the value for "noon versus morning" [13.1 ± 3.6 l/min], which is similar in magnitude to the "O_3 * noon" effect.)

The noon O_3 effect was increased in children with asthma; estimated as the sum of effects, (O_3 * noon and O_3 * noon * asthma) was −31.0 l/min/100 ppb (11.9 added to −19.1). The large variability (*SE* = 17.9) precluded statistical significance ($p < .10$). Part of this variability resulted from the reduced number of noon PEFR measurements, compared with other time periods. Thus, higher O_3 concentrations were related to marked suppression of the usual increase of PEFR early in the day. The O_3 effect on noon PEFR values was not significant when the 8-h mean was used to estimate O_3 concentrations (in Model III).

The effect of O_3 on evening PEFRs was seen only in asthmatic children, and it was more pronounced when the 8-h mean was used to estimate O_3 concentration instead of the 1-h maximum value (Table 1, Models III and II, respectively). This may have resulted from a delayed or cumulative response to O_3 during the course of the day. The PEFR values, estimated from Model II for 1-h maximum O_3, are illustrated in Figure 2. This essentially represents the diurnal change in PEFRs for two levels of O_3 in asthmatics (where 1 = asthmatics), compared with others.

Table 1.—Effects of O_3 on PEFR Values (l/min) Estimated in Random Effects Models

Factors in model	Ozone concentration (in 100 ppb) estimated as: 1-h maximum Model I	1-h maximum Model II	8-h mean Model III
Time-dependent			
O_3 * noon	−11.9 ± 6.3‡	*	*
O_3 * noon * asthma	(−19.1 ± 19.0)†	*	*
O_3 * evening	*	(0.2 ± 4.7)	(1.2 ± 5.4)
O_3 * asthma * evening	*	−13.8 ± 4.9	−17.6 ± 5.8
O_3 * ETS * evening	*	(−1.6 ± 2.6)	(−2.0 ± 3.1)
Constant			
Age (y)	25.1 ± 1.1	25.2 ± 1.1	25.2 ± 1.1
Noon (vs. morning)	13.1 ± 3.6	6.6 ± 1.0	6.5 ± 1.1
Evening (vs. morning)	8.0 ± 0.8	8.2 ± 2.6	7.8 ± 2.6
Asthma * morning	(−2.90 ± 2.4)	−10.9 ± 2.8	−11.3 ± 2.8
Asthma * noon	20.9 ± 11.7‡	*	*
Constant	55.7 ± 10.8	56.1 ± 10.9	56.1 ± 10.9

Notes: All subjects were 15 y of age or less. All values presented as coefficient ± standard error. Total number of subjects included = 287; total number of observations = 5 483.
*Not included in the model.
†( ) effects nonsignificant but included in the model.
‡$.05 < p < .10$; all other effects are significant ($p < .05$).

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Table 2.—Effects of O_3 on PEFR Values (l/min) Estimated in Random Effects Models

Factors in model	Ozone concentration (in 100 ppb) estimated as: 1-h maximum Model I	8-h mean Model II	8-h mean Model III
Time-dependent			
O_3 * evening	(−3.7 ± 3.1)*	(−3.8 ± 3.6)	†
O_3 * time out * evening	†	†	(0.3 ± .05)
O_3 * time out * asthma * evening	−2.3 ± 1.4‡	−2.9 ± 1.6‡	−4.5 ± 1.8
O_3 * during 4 preceding days * asthma	†	(−19.5 ± 18.2)	†
Constant			
Females (vs. males)	−145.2 ± 4.8	−145.3 ± 6.7	−143.9 ± 6.9
Evening (vs. morning)	14.7 ± 1.9	14.4 ± 1.8	12.0 ± 0.9
Asthma * morning	−7.8 ± 2.0	−7.8 ± 1.9	−9.8 ± 2.0
Females * evening	−2.8 ± 1.0	−2.8 ± 1.0	−2.3 ± 1.1
Environmental tobacco smoke	†	†	−16.4 ± 7.2
Constant	566.3 ± 4.8	567.1 ± 4.9	571.1 ± 5.6
No. of subjects	520	520	445
No. of observations	8 122	8 118	7 224

Notes: All subjects were 15+ y of age. All values presented as coefficient ± standard error, except as otherwise noted.
*Effects nonsignificant but included in the model.
†Not included in the model.
‡.05 < p < .10; all other effects are significant (p < .05).

In children with asthma, the estimated decrement in evening PEFRs resulting from an 8-h mean O_3 concentration of 80 ppb (Model III) was 4.3% of the mean evening PEFR level (calculated as before, age = 10 y). Another model (not shown, limited to 5 339 observations), which estimated O_3 exposure to be the product of the O_3 8-h mean and the duration of time spent outdoors during that day (expressed as ppb-h), showed a significant overall effect of O_3 exposure in asthmatic children (−4.9 ± 1.5 l/min/100 ppb-h) and an additional O_3-related decrement in evening PEFR level in children exposed to ETS at home (−2.1 ± 0.9 l/min/100 ppb-h).

In general, there was no significant relationship between morning PEFR values and ambient O_3 levels on the preceding day, although there was a tendency (not significant) for morning PEFR to decrease with an increasing 1-h maximum O_3 in asthmatic children; the variability of this effect was very large (-14.3 ± 14.8 l/min/100 ppb). No indication was found for an effect of cumulative O_3 exposure, estimated as an average of 8-h mean O_3 levels in 4 preceding days, and there was no difference between the results for asthmatic and nonasthmatic children.

In adults, no decrease in noon PEFR values was seen during the days when there were higher O_3 levels; the estimated effect of O_3, adjusted for sex, asthma status, and diurnal variability of PEFR was +6.1 (± 3.9) l/min/100 ppb (p > .10). There was, however, an effect of O_3 exposure (time * concentration) on evening PEFR—but only in asthmatics—and it was related to the amount of time spent outdoors on the days higher O_3 concentrations occurred (Table 2). The effects of 1-h and 8-h O_3 estimates were similar, and both were rather small. With regard to mean evening level, the effect of 100 ppb-h did not exceed 0.5% in men and 0.7% in women. In 445 nonsmoking adults who had ETS exposure, the effect of O_3 in asthmatics—adjusted for ETS—was more pronounced (Model II in Table 2). A similar effect of O_3 in asthmatics (−5.1 ± 1.9 l/min/100 ppb-h) was obtained for 305 subjects in whose homes there were no smokers (5 011 observations).

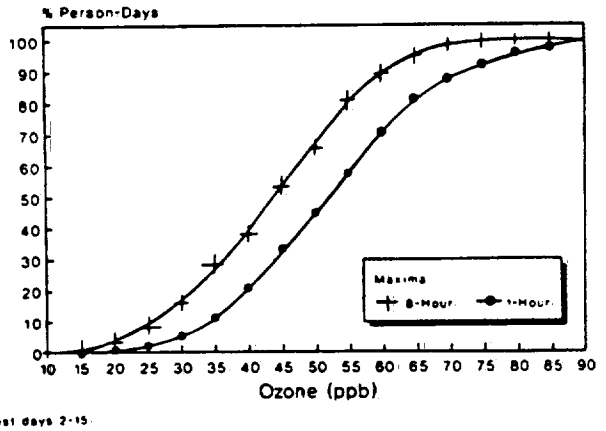

Fig. 1. Cumulative distributions of person-days by 1-h maximum and maximum 8-h mean O_3 concentration.

In adults, there was no significant decrement in morning PEFRs that resulted from higher O_3 levels during 1 or during the 4 preceding days (i.e., the same as was found for children). However, the effect of mean O_3 level during the 4 preceding days, estimated for asthmatics (−19.5 ± 18.2 l/min/100 ppb), suggested that there might be a tendency for a more lasting response in some individuals who have asthma. These results did not change after adjustment was made for ETS.

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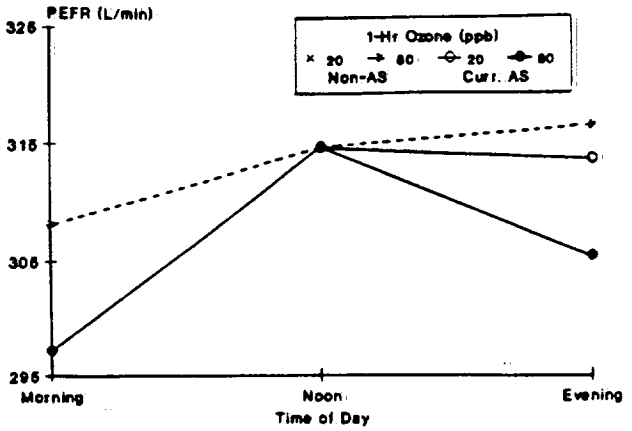

Fig. 2. Effect of 1-h maximum O_3 on evening PEFR in asthmatic and nonasthmatic children, estimated by random effect models (Table 1, Model II: age = 10 y).

The PEFR values were also related independently to some of the remaining covariables considered. In children, PEFR values were reduced by 5.6 (± 2.4) l/min on days when acute respiratory illness symptoms occurred. On hotter days, the evening PEFR levels were decreased in children (by 1.6 ± 0.6 l/min/10 °F), and noon PEFR levels were decreased in adults (by 2.7 ± 0.4 l/min/10 °F). However, these factors did not influence the relationship of PEFR with O_3. Furthermore, PEFR was not related to working near dusts or fumes or to ambient levels of PM_{10}, and there were no interactions between these factors and O_3. Results for subjects examined in March (the first month in each study year during which O_3 levels exceeded 50 ppb on most days) were not different from the results for subjects examined during other seasons.

Daily variations in PEFR and symptoms. Daily average evening PEFR was related to maximum 8-h O_3 during days in the spring, summer (without precipitation), and fall, after adjusting for significant covariables in the ANCOVA model (specifically, the proportion of children). The relationship of evening PEFR with maximum temperature was only of borderline significance (p = .08). The interactive effect of O_3 and temperature on daily average evening PEFR was also borderline (p = .07). However, the three-way interaction of O_3 * temperature * PM_{10} on daily average PEFR was highly significant (Fig. 3). Maximum temperature alone, and while interacting with PM_{10}, was significantly related to reduced PEFR. Increased days of observation (by removal of PM_{10} as an explanatory variable) enhanced the significance of the O_3-temperature interaction (to p = .005 [Fig. 3]). Ozone alone—above 56 ppb—produced a difference of more than 12 l/min; the three-way interaction led to a reduction of more than 21 l/min, which was not quite additive. The use of season-specific, age-adjusted z-scores (standard normal deviates) yielded similar results. Effects of O_3 from the previous day on average morning PEFRs were primarily in conjunction with the previous day's temperature and with PM_{10}.

There was a significant increase in symptoms associated with prolonged exposure to O_3, which was indexed as the maximum 8-h average on the previous day. The effect was seen primarily for allergic-irritant symptoms (Table 3). The increase was much greater with interactions of O_3 and maximum temperature and with PM_{10}. Ozone alone produced a difference of more than 7% in prevalence rates. There was also an increase in symptoms that resulted mainly from temperature; there was only a limited effect of prolonged O_3 exposure. After log transformation of symptom rates, the previous day's O_3 (i.e., lag one) and that day's maximum temperature were independently significant. There were no significant interactions. Other covariates and confounders (listed in the Methods section) were not significant in any of these ANCOVA models.

Discussion

This study shows that, for children (especially asthmatics), a reduction of PEFR, measured at noon on days when high peaks of O_3 concentration occur, is indicative of an immediate response of respiratory function to O_3 exposure. In children and adults, and especially asthmatics, we have also found similar effects of O_3 on PEFR levels measured in the evening (i.e., following several hours of elevated O_3 concentration in ambient air). Often this effect was much more pronounced when elevated on a daily basis, and it was related to interactions of O_3 with temperature and, sometimes, PM_{10}. Effects of O_3 on daily symptoms rates were also seen (specifically for allergic-irritant symptoms).

No major effect on PEFR (morning) was related to the previous day's O_3 in the REM analysis; however, a trend was suggested in asthmatics (random-effects model). Changes in daily average morning PEFR values were related to the previous day's 8-h O_3 in the ANCOVA analysis. Neither model revealed cumulative effects for the previous 4 d of O_3 exposure. A previous time-series analysis from a different Tucson population study had not shown a lagged effect of maximum 1-h O_3 on PEFR either, but had shown such lagged effects on productive cough (of 1–2 d) and wheeze (of 3 d) in asthmatics.[27]

It is possible that there are some longer-lasting effects of O_3 on lung function,[10] but that their magnitude is too smal to be detected in this analysis because of the variability of PEFR measurements. We performed a simulation study so that the minimum effects that were detectable with our data (REM method) could be evaluated. We assumed a linear change in PEFRs, related to O_3 concentration during the preceding day, and a mean linear coefficient B. The actual value of the coefficient, b, was selected for each individual as a random number, normally distributed with mean B and standard error $B/2$. We calculated, for each PEFR measurement, the expected value to be a sum of the actual value and b * (O_3 level in preceding day − 50 ppb). Several values of B were considered. The minimal simulated effect found to be significant for children by the random effects model was −12 ± 6 l/min/100 ppb. The minimal detectable effect in adults was −6 ± 3 l/min/100 ppb. The threshold values decrease when smaller variability of the effects is assumed. These results show that

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Table 3.—Effect of Prior Day's Maximum 8-h PM_{10} and Temperature on Daily Prevalence Rates (%) of Allergic/Irritant Symptoms

O_3 (ppb)	n	Adjusted* independent prev. rates (Lag one)	Interactions/variables: PM_{10} (μg/m³)† ⩽ 50	PM_{10} (μg/m³)† > 50	Max. temp. (°F)† ⩽ 70	Max. temp. (°F)† 70–95	Max. temp. (°F)† > 95
⩽ 56	210	25.8%	26.9%	24.1%	25.4%	28.1%	20.1%
> 56	52	32.7%	27.2%(27)‡	37.9%(25)	(1)	33.6%(33)	26.2%(18)
Adjusted* independent		Prev. rates	27.0	27.5	27.3	29.6	21.8
p (independent) = .011			ns			$< 10^{-3}$	
p (interaction)			.07			.03	

Note: Overall ANOVA: $p < 10^{-3}$ (R^2 = 18.2%).
*Adjusted for covariates (% children, smoking) and other explanatory.
†Max Temp — PM_{10} interaction significant, p = .03.
‡Number within parentheses denotes demoninator, when $n < 52$.

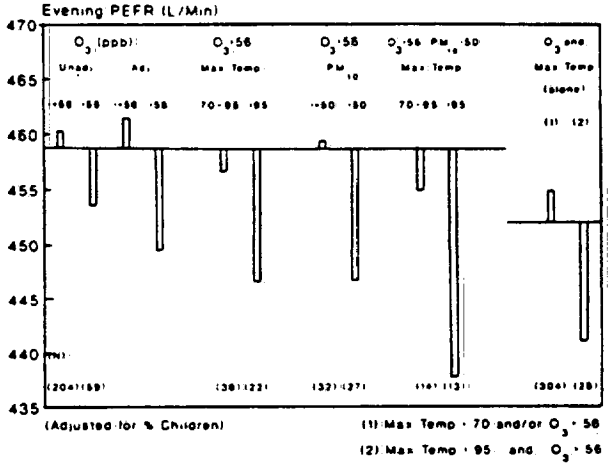

Fig. 3. Effect of 8-h O_3 on daily evening PEFR and interactive effects of O_3 with PM_{10} and temperature, estimated by ANCOVA models.

lagged effects could have been detected if their magnitude had been similar to or greater than that of the observed short-term effects.

On many occasions, the study subjects could not measure their PEFR because limited resources allowed for only one peak flow meter per home. Thus, only 52% of subjects had data for each day, and very few of them performed all three tests each day. We wanted to assess the effect of missing data on the relationships studied; therefore, the relationship between the proportion of completed measurements, O_3 concentration, and subject's PEFR level was analyzed. Such analysis indicated that the noon PEFR measurement was more likely to be omitted by adults who had lower mean PEFR levels on days when there were higher O_3 concentrations. This could be the reason for the observed slight increase in noon PEFRs on days when there was a high 1-h O_3 level, and might, therefore, lead to an underestimation of the effect of O_3 on noon PEFRs in adults. In children, the omission of the noon PEFR measurement was more likely to occur in those with lower PEFR levels, but that relationship was similar during days when there were various O_3 levels. We conclude, therefore, that the estimated effect of O_3 on noon PEFRs in children is not likely to be biased by the selection. Furthermore, there was no relationship between the frequency of days for which PEFR measurements were missing and the mean O_3 levels during the 4 preceding days, with respect to the PEFR average level. Therefore, missing data were not a factor in failing to detect prolonged-exposure effects.

The observed short-term effects of O_3 on noon PEFRs in children were greater than those reported previously in some chamber studies,[23-25] but they were smaller than the effects of O_3 on pulmonary function that were estimated in field studies.[3-5] Also, in adults, the magnitude of the decrement in PEFRs that resulted from O_3 was smaller than that found previously in a group of subjects who exercised.[6] One source of these differences may be the assessment of the O_3 exposure. We can assume that most subjects in this study had a lower level of activity than was observed or applied in former studies. The spatial distribution of O_3 concentrations in the Tucson basin was fairly uniform, but individual exposures could vary considerably because of the different patterns of daily activity. Subjects spent much of the day indoors, which possibly reduced their O_3 exposure; this would be especially true if they were indoors during the hours of higher O_3 levels. The information on time spent indoors included in the models only partially improved the estimate of exposure because this value did not identify the specific hours when the subjects were outdoors. (Subsequent studies in this population will enable examination of when the children are outdoors.) The different patterns of activity may explain, in part, the different responses to O_3 observed in children and in adults. Children may be more

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likely than adults to be outdoors around noon and before evening, and are more likely to be exposed to elevated levels of O_3 before the PEFR measurements. In adults, the effects of O_3 on evening PEFRs could result from prolonged exposure, but may also result from a short-term exposure that may occur in the afternoon, shortly before their evening PEFR measurement. It appears that the afternoon O_3 levels may be quite elevated during days when 8-h means are high.

In addition to this possible overestimation of O_3 exposure for some subjects in our study, another factor that could have contributed to a smaller function response seen here, compared with other field studies, may be the relatively low levels of air pollutants (other than O_3 and PM_{10}) in Tucson.[26] These pollutants—especially acid aerosols—may have increased the response in the previous field studies.[1]

This analysis indicates that a more pronounced response to O_3 exists in some adult asthmatics than in nonasthmatic subjects. An increased effect of O_3 was seen in asthmatics in the previous Tucson study[5,28] and in recent laboratory experiments,[29] but not in other data.[30,31] In the present study, there was an increase in O_3 effects attributed to asthma, but they were not always statistically significant. This was the case because of the large variability of the results in asthmatics; it is possible that an increased number of asthmatic subjects or an increased number of observations would produce more pronounced effects.

The use of medication improves morning values for asthmatics, but it has no effect on the relationship between other air pollutants and PEFR.[32] In the current study, the only significant correlation between medication use and level of O_3 was seen in male asthmatics who were 35 y and older: 48% used breathing medication on the days when there was 1-h O_3 levels of 65 ppb or more, compared with 19% on other days ($p < .01$). The corresponding percentages of subjects who used medications on days when there were 8-h O_3 levels of 65 ppb or more, versus days when there was less than 65 ppb, were 41% and 26%, respectively ($p < .01$). The use of medications on days when there were higher O_3 levels may have minimized our result in adults, especially in asthmatics. Use of medication increased PEFRs on days when there was low O_3, but it did not increase PEFRs on days when there was high O_3. An ANCOVA demonstrated that the effect of maximum 8-h O_3 on the reduction of PEFR was still significant ($p < .05$), but that the effect of the medication and the interaction of medication use with O_3 were not significant ($p > .10$).

The lack of a consistent cumulative effect of elevated O_3 for a few days could be expected if a functional adaptation of the respiratory system occurs, as was found previously for an O_3 concentration that exceeded 350 ppb.[33-35] However, such adaptation, if it exists, did not modify the short-term responses to O_3 in our study. Also, the analysis of seasonal effects does not support the hypothesis of a longer-lasting adaptation. Our choice of March as the possible time for a greater "spring" response was based on analysis of O_3 levels. Between November and February, the number of days during which maximum 1-h O_3 levels exceeded 50 ppb were only 3–10/mo, whereas in the remaining months this number exceeded 23. The lack of an effect of season in the REM analysis might have resulted from the crude identification of the time when an increased response to higher O_3 occurred, or perhaps from a too short time period in which there were low levels of ambient O_3. When daily values (in the ANCOVA) were restricted to the O_3 season in Tucson (i.e., spring, dry summer, fall), the effects were more evident than if using the entire year. Therefore, it is unlikely that negative findings would result from a small, but significant, adaptation process in the Tucson population.

The analyses also controlled for SES, crowding, cigarette smoke (ETS) exposure, gas stoves, and actual monitoring results. Our results, therefore, were not spurious, based on the exposure assessment used, nor were they based on uncontrolled effect-modifiers or confounders.

In conclusion, our results indicate that short-term effects of ambient O_3 at concentrations below the current standard (120 ppb) can be observed during the normal activity of a community population.

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